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MARINE METEOROLOGY

Cumulus Cloud Observations: Methods,
Instrumentation, Flight Procedures,
Reduction and Analysis of Data

By

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Abstract

The use of the PBY-6A aircraft in cumulus cloud observations is discussed in detail. The calibration of the aircraft for vertical draft measurements is reviewed and its applicability to cloud penetrations established. The equation for draft calculation from oscillograph records of accelerations, pitch, airspeed, and altitude is set forth and its use with the actual records outlined. The other measurements made in cloud flights, including temperature, water vapor, liquid water, small-scale turbulence, and those by photography, are described, along with the instrumentation employed. An estimate of the instrumental lags and errors is given where possible. The cloud-flight procedures, stating the role of each observer and the method of flying are outlined, and the steps in the reduction and analysis of the data presented, including the reconstruction of the final cloud cross sections with the aid of photographs. It is shown why the PBY is probably the only satisfactory aircraft for this type of meteorological work.

I. INTRODUCTION

In the course of our efforts to study the structure and development of cumulus clouds it has become necessary to obtain measurements of the internal properties of the clouds in relation to those of the environment air. Some of the most important quantities to measure are: vertical and horizontal drafts; the development of small-scale turbulence; temperature and water vapor content of both cloud and ambient air; free water content of the cloud; its slope in the plane of the wind; and the wind profile of the environment.

The basic tool of all these measurements has been a PBY-6A amphibian aircraft, obtained by the Woods Hole Oceanographic Institution on loan from the U. S. Navy through the Navy's Bureau of Aeronautics and Office of Naval Research. This aircraft is used both as an observing platform to carry the sensing instruments into and through the clouds and as a calibrated measuring device in itself.

It is in general desired to obtain a profile of the various parameters in a cross section through the cloud at several different levels. These cross sections are commonly made approximately in the plane of the ambient wind in the manner illustrated in Figure 1. The runs are made in alternate directions from the top downward at the normal flying speed of the aircraft, namely 50-60 m sec^{-1}. It was found in practice that 6-7 runs each of 1-2 minutes duration could be completed in 15-20 minutes time. The individual runs are put together into the cross section of the cloud (example shown in Figure 2) primarily with the aid of coded sidemarks which appear simultaneously on all records, supplemented by several types of photographs. Before discussing further the final reconstruction of the data, however, each measurement and instrumental procedure will be described individually. The

heart of the program, as of the cumulus itself, is the vertical draft. The method of vertical velocity determination will therefore be discussed first.

II. VERTICAL AND HORIZONTAL DRAFT MEASUREMENTS

The vertical draft measuring technique is based upon a fast-responding accelerometer which records the normal accelerations of the aircraft. From integration of the accelerometer record, the vertical motion of the aircraft may be obtained and if its rising or sinking speed is calculable, the vertical velocity of the air is then determined. The soundness of the accelerometer method for this aircraft has been established by Brewer (1954) who performed numerous tests which showed that a) a fuselage-mounted accelerometer accurately records the gust loads applied by the air to the wings and b) integration of the accelerometer records gives the vertical motion of the aircraft under turbulent conditions. This latter point was established by the agreement between integration of the accelerometer records with differentiated records of a sensitive altimeter.

Carrying on from Brewer's work, Bunker (1953) has worked out an expression for the sinking (or rising) speed of the aircraft relative to the air in terms of readily recorded auxiliary measurements, namely airspeed and pitch angle. He has shown that the equation for the vertical velocity of the air, w', over a given short interval of time, t_i, is

$$w' = \frac{\Delta n' V_t M}{\frac{1}{2}\rho \bar{V}^2 S \dfrac{dC_L}{d\alpha}} - \frac{4MgV_t \, \Delta V_t}{\rho \bar{V}^3 S \dfrac{dC_L}{d\alpha}} - \Delta\alpha_{att} V_t + \sum \Delta n' t_i \qquad (1)$$

where M, S, and $dC_L/d\alpha$ are constants of the airplane: namely mass, wing area, and variation of the lift coefficient with angle of attack. These are

known for the PBY and have the following values:

$M = 1.34 \times 10^7$ gm (varies with gas load, etc. $\pm 0.05 \times 10^7$ gm)

$S = 1.30 \times 10^6$ cm^2

$dC_L/d\alpha = 4.54$ (see Brewer, 1954, loc. cit. and Bunker, 1953)

The air density, ρ, may be taken from the psychrograph soundings (see McCasland, 1951); g is the acceleration of gravity; $\Delta n'$ is the normal acceleration of the aircraft; $\bar{V}$ is the average true airspeed over the entire run; V_t is the true airspeed during t_i; ΔV_t is the departure from a zeroed or averaged value (to be discussed); and $\Delta\alpha_{att}$ is the departure in pitch angle from the average value during the past ten seconds. All units are c.g.s.

The assumptions upon which this equation is based and its validity under turbulent conditions have been established and discussed by Bunker in the report previously cited. It is readily seen that his conditions apply to cumulus cloud flights, except possibly the one which states "the gust is sharp-fronted and symmetrical across the span of the wing". Bunker found it possible to correct for the degree of gust penetration by multiplying the observed Δn by 1.1 to obtain $\Delta n'$. Weights for each degree of gust penetration were found from the accelerometer record of a flight through an atmosphere with a turbulence typical of that desired for study. The weights used were the averages over the entire flight of the absolute values of the average accelerations for each degree of gust penetration. A similar procedure was applied to a typical cumulus cloud flight and the results compared to Bunker's (Figure 3). It is seen that the distributions of gust penetrations are nearly identical and thus the averaging may be expected to give the same results. This conclusion is independent of the coincidence that in

the cases examined the peak accelerations are nearly identical, since the weighting procedure depends only upon the distribution of the gust penetrations relative to the maximum value.

Therefore, introducing all the known constants, equation (1) becomes identical to Bunker's

$$w' = 4.98 \frac{\Delta n V_t}{\rho \bar{V}^2} - \frac{8.9 \times 10^3 \, V_t \Delta V_t}{\rho \bar{V}^3} - \Delta\alpha_{att} V_t + \sum 1.1 \Delta n t_i \quad (2)$$

where Δn is now the measured normal acceleration. The time interval t_i is chosen as one-fifth second since Brewer's work showed that this included the smallest gusts to which the PBY responds (10-12 m). It will be noted that if ΔV_t and $\Delta \alpha_{att}$ are zero, i.e., the aircraft is flown at constant airspeed and constant attitude, its sinking speed is given by the first term above. The vertical motion of the aircraft relative to the ground is given by the last term, namely the integrated accelerations. The early sets of cloud records (see Malkus, 1954a) were obtained under these restrictions, with the pilot giving special care to the flight technique, since the equipment to measure airspeed and attitude fluctuations had not been introduced. It was shown by calculations on later records that the corrections for airspeed and attitude average out to very small values over an entire draft 200-500 m in horizontal extent, being about 15-20 cm/sec for a draft averaging 150-300 cm/sec, or about 10%. For the short-period readings, however, these corrections are very important; the pitch variation, if neglected, generally causes the far larger error. For the airspeeds flown, each degree deviation in pitch (from the average value over the past ten seconds) gives about $\pm$ 100 cm/sec correction to the one-fifth second values of w'. Therefore

runs showing pitch variations of as much or more than 3° were in general discarded as unreliable unless very high velocity drafts ($\sim$10 m sec^{-1}) were being studied. Furthermore, at pitch angles of 3° or more from level attitude, the airplane is in climbing or descending flight: the Δ n is no longer strictly a vertical acceleration and the airspeed will be characteristic of climbing or descending flight rather than the gusts encountered. It is therefore mandatory not only that the aircraft be flown with very small departures from constant attitude, but that the flight attitude not depart at any time from level flight by more than about 3°, in order that the corrections applied to the records due to aircraft performance shall not exceed the magnitude of the drafts being measured. These rather stringent requirements have been met on about 50% of the cloud flights obtained so far.

The airspeed records are used to obtain the airspeed correction for w' in equation (2) and also to evaluate horizontal gusts approximately. Since the region outside cumuli (especially their upper portions) is generally free from turbulence, the airspeed in the clear air is taken as the zero or undisturbed value. Departures from this value are used in equation (2) to obtain the airspeed correction to w'. For airspeed fluctuations of $\pm$ 100 cm/sec, the correction to w' is about $\mp$ 25 cm/sec, which are extreme values encountered. Horizontal gusts or drafts are evaluated as follows: the aircraft is assumed to hold a constant ground speed over the 60-100 second run. If the flight is into the wind, an increase in airspeed above the outside clear air value means an increase in windspeed of this amount, etc. The assumption of constant ground speed over these intervals is now being tested by Bunker.

Bunker (1954) has shown, in part by independent tower determinations, that the w' values obtained by the method outlined are probably reliable to 10-15%. Concerning the horizontal gusts, or u' values, confirmation exists in the excellent agreement between Bunker's very low-level shearing stresses, which involve the direct product u'w' and those made at the ground by a Sheppard-type plate (see the Summary of Observations Made at O'Neill, Nebraska, 1953, edited by Thornthwaite, Halstead, and Mather). While this indicates the correctness in phase and sign for u', the problem of correct zeroing for these records is not yet too soundly solved.

All the instruments used in vertical velocity determination, namely strain gauge accelerometer, gyro for pitch determination, and sensitive airspeed meter record photographically on a C.E.C. nine channel oscillograph. In addition, a sensitive altimeter (described by Brewer, loc. cit.) also records thereon. This is to assure that the integration is always begun sufficiently far from the cloud so that no initial vertical velocity is present. A typical record through a small cumulus humilis (9 seconds or 500 m across) is presented in Figure 4. The peak acceleration observed was 175 cm/sec^2. The maximum deviation from level flight on the pitch trace is less than 2°, and the maximum airspeed departure from the initial is 120 cm/sec. The most altitude gained or lost by the aircraft is 70 ft. This cloud (photographed in Figure 5) possessed updrafts of peak magnitudes only about 1 m sec^{-1} and liquid water content a maximum of 0.1 gm/m^3.

III. DETERMINATION OF SMALL-SCALE TURBULENCE

The relative development of small-scale turbulence within and near the clouds is determined by obtaining a quantity called the "turbulence index".

This is calculated by planimetering the envelope of the accelerometer curve over five second intervals. The resulting area is the turbulence index for that interval. This parameter was first defined by Malkus and Bunker (1952) and was found very useful in describing the relative "roughness" of the air. Since clearly the magnitudes of accelerations experienced will depend on the particular aircraft used, these values will only have significance in comparison to one another and not in an absolute sense.

IV. MEASUREMENT OF TEMPERATURE AND WATER VAPOR CONTENT

The basic instrument for these determinations is a modified form of the M.I.T. psychrograph, described in a previous report by McCasland (1951) and to be described further in a forthcoming report by Bunker. The sensing elements consist of two thermistors, one with a saturated wick, which determine the wet- and dry-bulb temperature of the air. This instrument has proved reliable and accurate and the main problem in using it on cloud flights concerns the question of the dynamic corrections to be applied, since the dry-bulb will become wetted within clouds and the dry-bulb correction (which has been obtained in clear air flight tests) will no longer be applicable. The procedure employed is as follows: the dry and wet dynamic corrections are applied to each record strictly as in clear air flights. Within clouds, therefore, the dry-bulb reading generally dips below the wet-bulb at or soon after cloud entrance. When this occurs, the cloud air is assumed 100% saturated and the wet-bulb reading alone (with wet-bulb correction) is used as the cloud temperature. It would be highly desirable to check this assumption of 100% relative humidity within cumuli by independent measurements, but failing in this so far, the extreme consistency of the records obtained,

with one another and with updraft calculations based on the steady-state cumulus model (see Malkus, 1954a) justifies the procedure to some extent. Another possible source of error is that the droplets encountered by the wet-bulb may have fallen from a higher region in the cloud and, being colder than the nearby air, may thus give rise to erroneously low temperatures. Since precipitating clouds and clouds with large drops and very high water contents have so far not been studied by the PBY, it is unlikely that this source of error has been operative. All the measurements described herein become more dubious in very large, violent, and heavily precipitating cumulonimbus clouds.

The wet- and dry-bulb temperatures are recorded on a Leeds and Northrup Speedomax potentiometer, which automatically switches between wet and dry readings every five seconds. These records are sidemarked simultaneously with those of the oscillograph and it is thus simple to match the temperature and water vapor values to the drafts. The lag of the dry and wet temperature readings is, however, about one and two seconds, respectively. The psychrograph thus integrates space-wise over a much larger interval than has been necessary on the draft determinations. Work is under way at present to develop faster-responding temperature and humidity sensors for use in the PBY.

With the aid of a spiral psychrograph sounding in the nearby clear air to give the pressure-height relation, the dry- and wet-bulb readings are used, together with several nomograms, to obtain mixing ratio, virtual temperature, and other desired parameters during each horizontal traverse through the cloud and its nearby surroundings. Then all the measurements for each traverse are generally plotted simultaneously on a single graph, as in the example shown in Figure 6.

V. MEASUREMENT OF THE LIQUID WATER CONTENT OF THE CLOUD

The liquid water content meter used in the PBY is so far still in the flight-testing stage. Through the courtesy of Dr. E. G. Bowen of the Commonwealth Industrial and Scientific Research Organization of Australia, an Australian-built liquid water content meter was given to this project. The operation of this instrument is based upon the measurement of the resistance changes of a paper tape on being moistened by cloud droplets which impinge directly upon it. This instrument has been described in a publication by Warner and Newnham (1952). An identical Australian instrument was simultaneously received by the Cloud Physics Project of the University of Chicago, who have done most of the calibration and testing of the device utilized in the PBY.

The instrument has been mounted on an airfoil about $3\frac{1}{2}$ ft below the wing of the PBY in the manner shown in Figure 7. This distance was chosen since it exceeds three times the wing chord ($\sim$1 ft) and therefore the slit is in a flow region undisturbed by the aircraft body or wing. The results are recorded on the oscillograph and a typical record appears in Figure 4. The paper tape used was kindly loaned by the Chicago Cloud Physics Project and the calibrations employed in proceeding from paper resistance to water content were carried out in their laboratory. Paper speeds ranging from .07 in/sec to five times this rate have been found suitable for the cumuli studied so far, the higher rates being necessary to prevent the readings from going off scale in the wetter clouds. The record shown in Figure 4 was made at the slowest speed, while the wettest cloud studied so far ($\sim$ 1.4 gm/m^3 maximum liquid water) required a paper speed four times this.

As described by Warner and Newnham (loc. cit.), a delay between water

collection and its recording has been introduced by mounting the electrical contacts about 2 in. from the slit. This delay is intended to permit the water drops to be absorbed by the paper. It amounts to 28 sec at the lowest paper speed, reducing proportionately as the paper drive is speeded up. In the case of small, rather dry clouds like the one illustrated in Figure 4, most of the delay time is in clear air flight. This is unfortunate, since tests made by the Chicago group[1] show that about 20% of the collected water will have evaporated during this time, so that the cloud water content recorded in the example is probably that much underestimated. When the paper speed is increased by a factor of 3-5, the delay is sufficiently short so that 10% or less of the collected water is lost by evaporation even if the delay occurs entirely in the clear. The regions of high water content in the larger clouds generally appear on the record before exit from the cloud and thus no losses due to evaporation may be expected except near the latter part of the record.

We do not know as yet the actual lag of this instrument, nor how much space integration it performs, although the records taken to date show micro-structure consistent with the smaller drafts ($\sim$ 200 m across), so that it is probable that in practice the lag does not exceed about three seconds.

VI. THE USE OF PHOTOGRAPHS TO DETERMINE THE CLOUD SLOPE AND IN THE FINAL RECONSTRUCTION OF THE DATA

Two types of aerial photography are employed as routine on the PBY. First, still shots are commonly taken in a precise manner to obtain the cloud slope in the plane of the wind, and simultaneously its shape and dimensions in the flown section. This is done by a Speed Graphic which is mounted at

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[1]Unpublished data on file with the Cloud Physics Project, Department of Meteorology, University of Chicago.

right angles to the fuselage in such a way that it always remains level. Preparatory to making the first cloud traverse of Figure 1, the aircraft flies downwind past the cloud at a distance of 2-3 miles and at the same elevation as the first run. The photographs are made on this leg and if cloud base is visible in the picture, the cloud may be reconstructed to scale from the print, since the height of the center line of the negative is the height of the aircraft. A typical photograph taken in this manner is shown in Figure 8. This was used in conjunction with a set of runs like Figure 6 in the construction of the completed cross section shown in Figure 2 in the following way: the photograph was reconstructed to scale on a large sheet of graph paper with horizontal lines drawn at each level traversed. When the coded sidemarks (transformed into vertical lines denoting cloud entry and exit on the individual traverses) indicated entry into the visible cloud, the within-cloud part of the traverse was begun within the cloud outline on the graph paper. In the example given, each run fell on the outline so that cloud exit occurred automatically at (within 25-50 m) of the photographed cloud boundary, and each run fell coherently below its predecessors, the updrafts coinciding with the depicted towers, so that no subjective juggling was necessary. Not all the clouds studied reconstructed so easily, since on occasion a few minutes elapsed between photography and traverses, or a slight deviation of the flight path from the photographed plane occurred. In these more difficult cases, the time-lapse motion pictures were used to aid the reconstruction.

The time-lapse pictures were taken from a wide-angle (146°) camera mounted in the nose turret and aimed straight forward. The lens for this camera arrangement was devised by Dr. William S. von Arx of the Woods Hole Oceanographic Institution, who has described its construction and use (1953).

Frames are exposed at a rate of 72 per minute and slides are manually inserted in the view field at the beginning of each traverse to denote the altitude, heading, and other pertinent information. Selected frames from a typical set of cloud runs are shown in Figure 9.

Recently a K-20 aerial still camera has been acquired for the PBY and may in the future partially supplant the Speed Graphic. It was used in obtaining Figure 5, which was not, however, obtained in the precise manner described above.

Additional quantitative cloud studies by photography have been made, using a combination of aerial still photography and time-lapse photography from the ground. It has on occasion been possible to photograph the same clouds simultaneously from known points at the ends of a base line, and so to obtain an accurate height and distance scale to be applied to the frames of the time-lapse pictures, in order to calculate rates of rise of cloud towers or their horizontal travel. Some results of this part of the program have been discussed by Malkus and Ronne (1954).

VII. DETERMINATION OF THE AMBIENT WIND PROFILE

When pilot balloon runs have been available within 20-50 miles and 1-2 hours of the cloud studied, these have been used to obtain the wind field. Since local variations, even in the trade-wind region, occur over these time and distance intervals, a method of wind determination by double-drift of the aircraft has been worked out and is now being developed further by Bunker, using a motion picture camera aimed downward through the aircraft's drift grid so that the records may be evaluated later in the laboratory. These techniques and their use will be presented in a later report of the

project. It is thus hoped to obtain the wind profile in the near vicinity of each cloud studied.

VIII. FLIGHT PROCEDURES

Ideally, four trained observers (in addition to the regular four-man crew of pilot, co-pilot, radio operator, and engineer) are required to carry out the cloud flights. Their observing stations are as follows: one in the nose turret forward of the pilots' cockpit to wind the nose camera drive, insert the notes, and otherwise monitor its operation; one in the navigation compartment to monitor the psychrograph; one in the bunk compartment to monitor the oscillograph, keep all the traces on scale and clear of one another and to turn the oscillograph on and off; and one in the blister compartment to direct the pilots, give the signals for the commencement of each run, sidemark the records in code for cloud entry, etc. and to keep copious notes. An additional person in the blister compartment is desirable, to take the Speed Graphic still pictures on the downwind leg before cloud entry. This can, however, be managed by the one blister observer, if necessary, and in a pinch one person can monitor both oscillograph and psychrograph (with the aid of radio operator). Since the nose camera will run by motor for short intervals, this means the minimal scientific crew for the cloud runs is two persons. This arrangement is, however, highly nerve-wracking.

Under ordinary conditions, the cloud to be studied is chosen jointly by pilot and blister observer. The pilot climbs the plane to a height usually near the cloud top, and after the downwind leg for the still pictures, makes a 180° turn into the wind in such a manner that he will be heading for the core of the cloud and will at the end of the turn be about 30 seconds away from it. He is then able to give the oscillograph observer a 30-second

warning through the interphone. He next levels and trims the ship, reads off the heading, airspeed, and exact altitude which are to be recorded by the blister observer, and gives another warning 15 seconds before cloud entry. At this point, the oscillograph is turned on. After exit from the cloud, the oscillograph is kept on for about 30-45 seconds to allow for the delay time in the liquid water collector. On occasions, the duration of clear air flight before cloud entry is extended, but since the oscillograph paper is consumed at the rate of one-half inch per second, it cannot be allowed to run continuously as can the psychrograph, which uses only 3 inches of chart paper per minute. At the end of each traverse the oscillograph run number is recorded by the blister observer, along with his other notes and code made during the run. At one time it was attempted to replace some of the note-writing by use of a wire recorder, but the work in transcribing the records did not prove to be recompensed by the information added. As a rule, the last run for each cloud is made skimming just below cloud base, although often an additional run 500 or 1000 ft lower is carried out.

Several variations upon this standard procedure have been made from time to time. Oftentimes it is desired to make several repeated passes at the same level in the cloud to determine variations in the structure with time. These are done in rapid succession in alternate directions. Occasionally it is desirable to make several traverses through the tower as it rises. This is a more difficult feat and so far no satisfactory records have been obtained. On rare occasions it is possible to make two complete sets of runs through the same cloud from top to bottom. One case of such data is so far on record, with one hour elapsing between the commencement time of the two sets. Sometimes it is desirable to make runs including two

or more clouds in a line, although the final reconstruction of such runs into a profile proves difficult.

The question naturally arises, especially in the case of the repeated runs through the same cloud at the same level, as to how much the entrance of the aircraft disturbs or alters the cloud structure. Often in the case of the weaker clouds it is obvious visually that the aircraft has had, at least temporarily, a destructive effect and on some occasions the roundish hole left by passage of the plane is visible on the nose camera films. At other times and in the case of stronger clouds (not necessarily larger clouds) no apparent effect or disturbance can be detected.

IX. CONCLUDING REMARKS AND FUTURE DEVELOPMENTS PLANNED

It is hoped to improve and augment the PBY instrumentation for cloud flights in the following ways:

1. More accurate zeroing for the horizontal draft determinations.
2. Faster responding temperature and water vapor sensors.
3. Further development of the present liquid water content meter to determine its lags and accuracy, with possibly the addition of an independent checking measurement.
4. Further development of the wind profile determination by double drift.
5. Addition of devices to measure drop size, drop size distribution, and electric space charge.

Several points must be emphasized in conclusion. Firstly, the PBY is probably the only aircraft in existence which would be suitable for the work described herein, having simultaneously rigidly mounted wings so that gust loads are accurately transmitted to the fuselage, very high frequency

wing whip, slow cruising and stalling speeds, high weight carrying capacity, and excellent visibility and safety characteristics.

Secondly, the development of the instrument program and flight procedures has taken the efforts of many people over at least six years and their further evolution to include the improvements listed above will consume several years more. The present state of the program is such, however, that cloud records are continually being taken and satisfactorily utilized in computations to check theoretical predictions and to suggest new lines of theoretical development.

X. ACKNOWLEDGMENTS

Many persons have contributed far more valuably than the writer to the development of the observation program described herein. Outstanding especially are Andrew Bunker, Given Brewer, and Kenneth McCasland, the latter of whom designed or adapted the majority of the instruments used. The photographic program was originated and carried out by Claude Ronne; the aircraft has been maintained and skillfully flown by a well-practiced civilian crew under the direction of Chief Pilot Norman Gingrass; the data has been worked up by Mary C. Thayer and Martha Walsh, who devised and improved several of the procedures.

Our appreciation and gratitude are owed to the Cloud Physics Project of the University of Chicago, who have generously aided us in the use of the Australian water content meter, and to the Radiophysics Laboratory, C.S.I.R.O., Australia, who originally made the instrument available to us. Thanks are also owing to many machinists and technicians, to anonymous officers and personnel of several Air Force Bases and Naval Air Stations who have housed, repaired, and fueled the PBY on its travels, and to many other organizations

and individuals who have helped us and provided advice, assistance, and equipment during the various phases of the work.

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TITLES FOR ILLUSTRATIONS

Fig. 1. Schematic diagram illustrating the manner in which cumulus clouds are ordinarily traversed by the PBY. One earlier run is generally made (commonly downwind) past the cloud at a distance of several miles from it, so the cloud can be photographed in the plane of the wind. Topmost run is made at same level at which photograph is taken. After Malkus (1954a).

Fig. 2. Example of the reconstructed cross section of an actual cumulus studied. Solid curves are vertical draft velocities (running mean values over 150 m distance) with origin being thin horizontal line at each level. Dashed lines are temperatures, assuming saturation within cloud boundaries, so that inside cloud the wet-bulb temperatures are used; dry-bulb temperatures are represented outside; x-ed lines are mixing ratios. Figures to far right are environment wet-bulb temperature, mixing ratio, and dry-bulb temperature, respectively. Latter two are taken as values of origins of x-ed and dashed curves. Calculated slope of cloud (see Malkus, 1954a) is given by heavy curved line. Winds obtained by double drift of aircraft are shown by arrows at the extreme left. Draft structure of this cloud is quite characteristic of nearly all trade cumuli studied so far, even after great improvement of draft measuring techniques since its time. After Malkus (1954a).

Fig. 3. Comparison between the degrees of gust penetrations observed by Bunker (1953) in a turbulent atmosphere and those found for a typical trade-cumulus cloud run (3500 ft, April 7, 1953, near Puerto Rico). The values plotted were obtained from the accelerometer record by taking

the average (absolute) accelerations over the indicated time intervals, ranging in the cloud case from 1-16 sec. The weighting procedure has been described by Bunker (loc. cit.).

Fig. 4. A typical oscillograph record (made on July 22, 1954, over land near Woods Hole, Mass.) through a small cumulus humilis. The run was made at 3100 ft, downwind, at 105 knots indicated airspeed. The time marks are full seconds, tenths of seconds being vertical lines on the oscillograph paper which do not show up in the reproduction. Values for each trace are positive downward. The coded sidemarks appear at the bottom, the long dash indicating cloud entrance, the three short dashes indicating exit. The space charge trace appearing is from an instrument still in the experimental stage. The remaining traces are from instruments described in the text. Notice the long delay in the liquid water trace, which should be moved backward 28 sec to occur within visible cloud.

Fig. 5. Photograph of the cloud traversed in Fig. 4 made by the K-20 aerial camera. This photograph was not made in the precise manner described in the text and was obtained only to show the general appearance of the cloud.

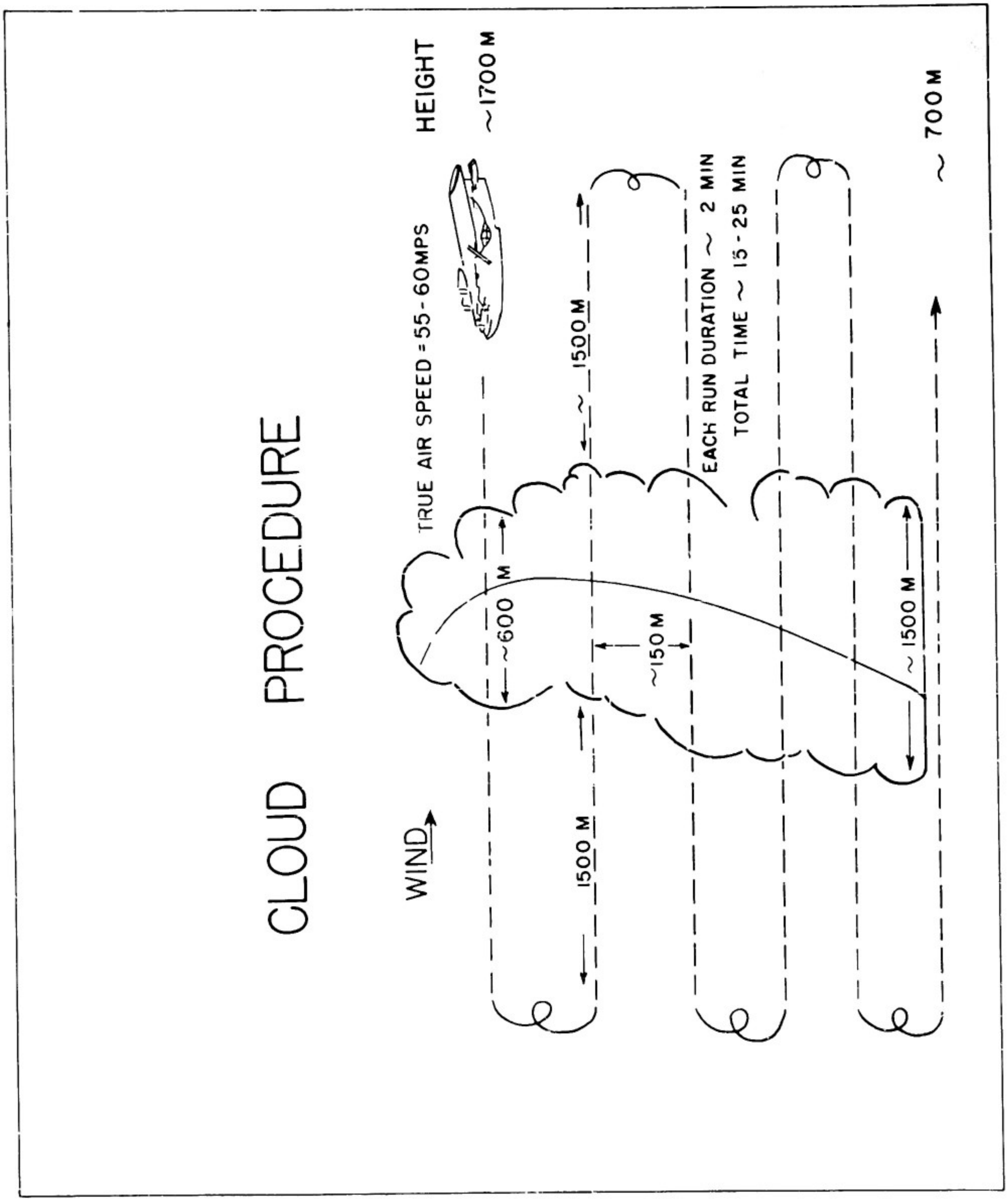
Fig. 6. Final plotting of a typical cloud traverse. The run was made upward (from right to left). T_d and T_w are the dry- and wet-bulb temperatures reduced directly from the psychrograph as described in the text. After the dry-bulb reading dips below that of the wet-bulb the cloud is assumed saturated at temperature T_w. T_v is the virtual temperature and q, the mixing ratio calculated from T_d, T_w, and the pressure. The vertical draft values were obtained in this case from the accelerometer records under

the assumption of constant airspeed and attitude. The heavy line shows results from integrating accelerations read off every 25 m, dashed curve being running averages of six of these values. Bottom curve, T.I., is turbulence index obtained in manner indicated in text. This run was one of the six used in constructing Fig. 2. (After Malkus, 1954a.)

Fig. 7. Photograph showing the mounting on the PBY of the Australian liquid water content meter on an airfoil suspended from the bomb rack. The collecting slit is at the forward edge of the triangular projection and the paper tape runs out below. The projecting tube from the wing is the pitot static head to which several meteorological instruments are connected.

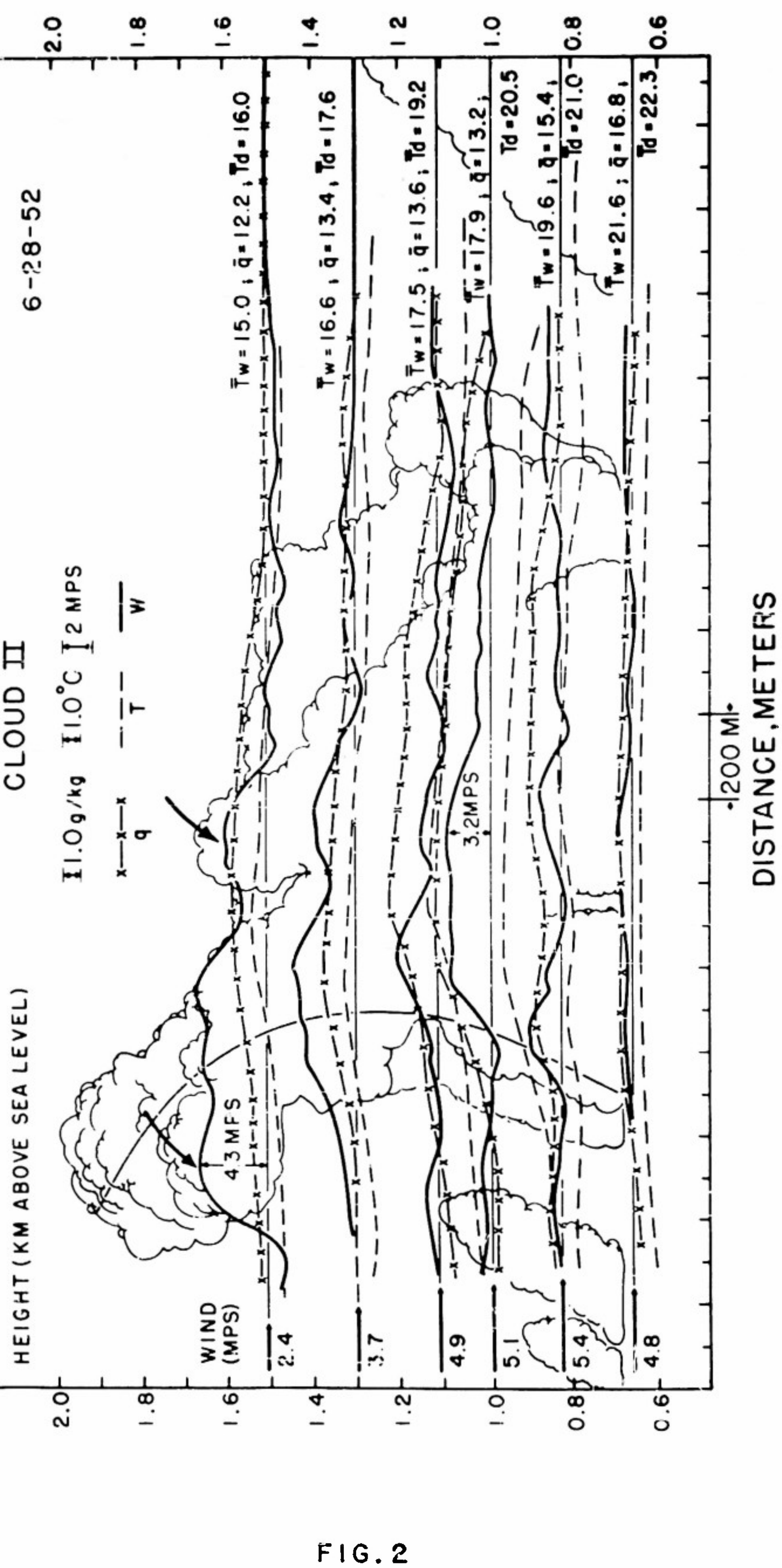
Fig. 8. Speed graphic photograph of the cloud studied in Figs. 2 and 6. This photograph was taken in the precise manner described in the text and the cloud outline in Fig. 2 was reconstructed to scale from it. The wind blows from left to right (east-southeast). (After Malkus, 1954a.)

Fig. 9. Selected frames from a typical set of cloud runs (over ocean near Puerto Rico April 7, 1953) made by the nose camera. Each vertical column comprises one traverse of the type shown in Fig. 6. The left-hand column shows the first or top traverse. The bottom frame on each traverse shows the beginning of the 180° turn just before the start of the descent at the end of the run. The data on this cloud has been worked up and is reported on by Malkus (1954b).



CLOUD PROCEDURE
TRUE AIR SPEED = 55-60MPS
HEIGHT
~1700 M
WIND
1500 M
~600 M
~150 M
~ 1500 M
EACH RUN DURATION ~ 2 MIN
TOTAL TIME ~ 15-25 MIN
~ 1500 M
~ 700 M

FIG. 1



CLOUD II
6-28-52
1.0 g/kg
1.0°C
2 MPS
q
T
W
HEIGHT (KM ABOVE SEA LEVEL)
WIND (MPS)
2.4
3.7
4.9
5.1
5.4
4.8
4.3 MPS
3.2 MPS
T̄w = 15.0 ; q̄ = 12.2 ; T̄d = 16.0
T̄w = 16.6 ; q̄ = 13.4 ; T̄d = 17.6
T̄w = 17.5 ; q̄ = 13.6 ; T̄d = 19.2
T̄w = 17.9 ; q̄ = 13.2 ; T̄d = 20.5
T̄w = 19.6 ; q̄ = 15.4 ; T̄d = 21.0
T̄w = 21.6 ; q̄ = 16.8 ; T̄d = 22.3
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
200 M
DISTANCE, METERS

FIG. 2

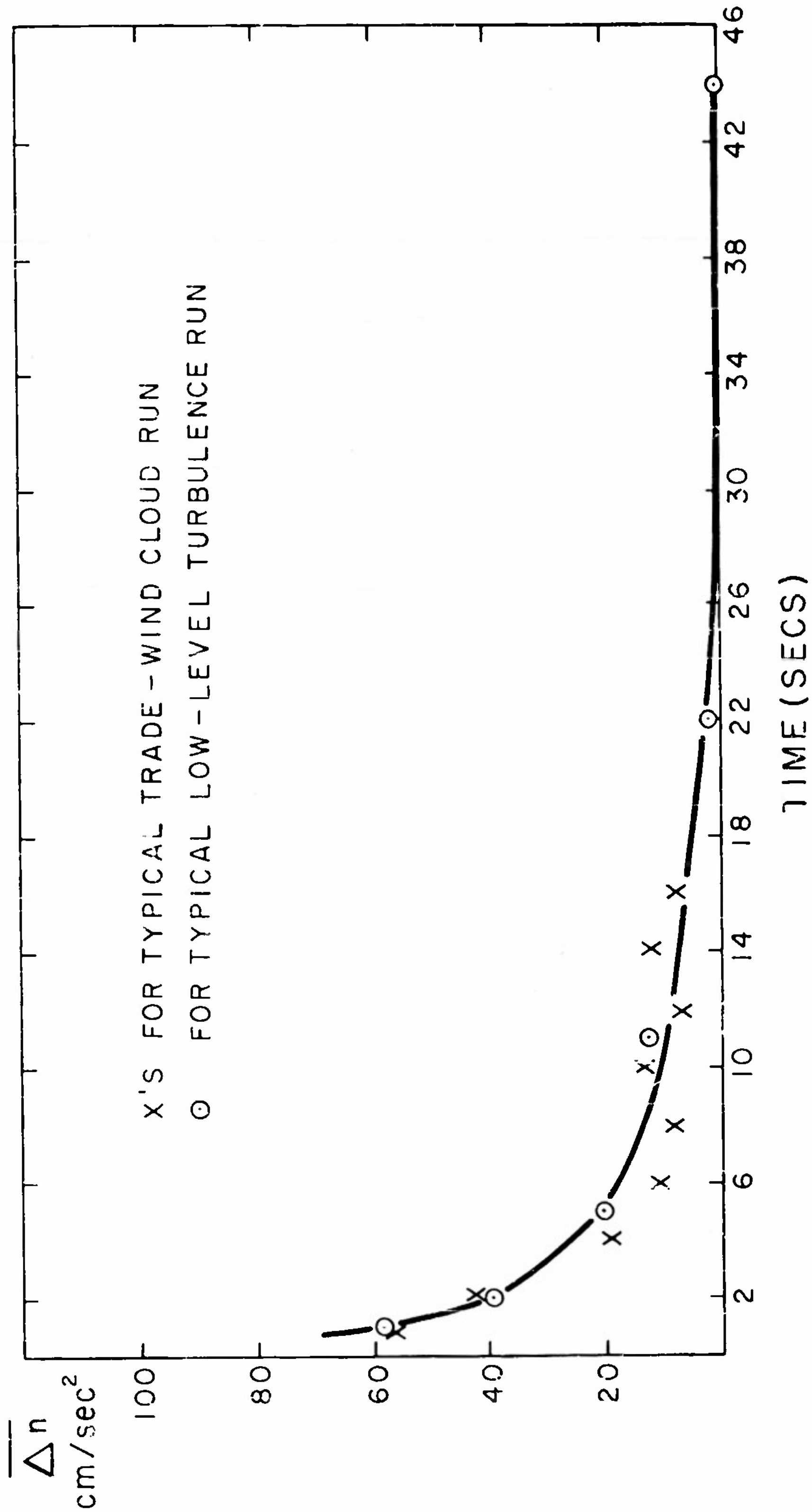
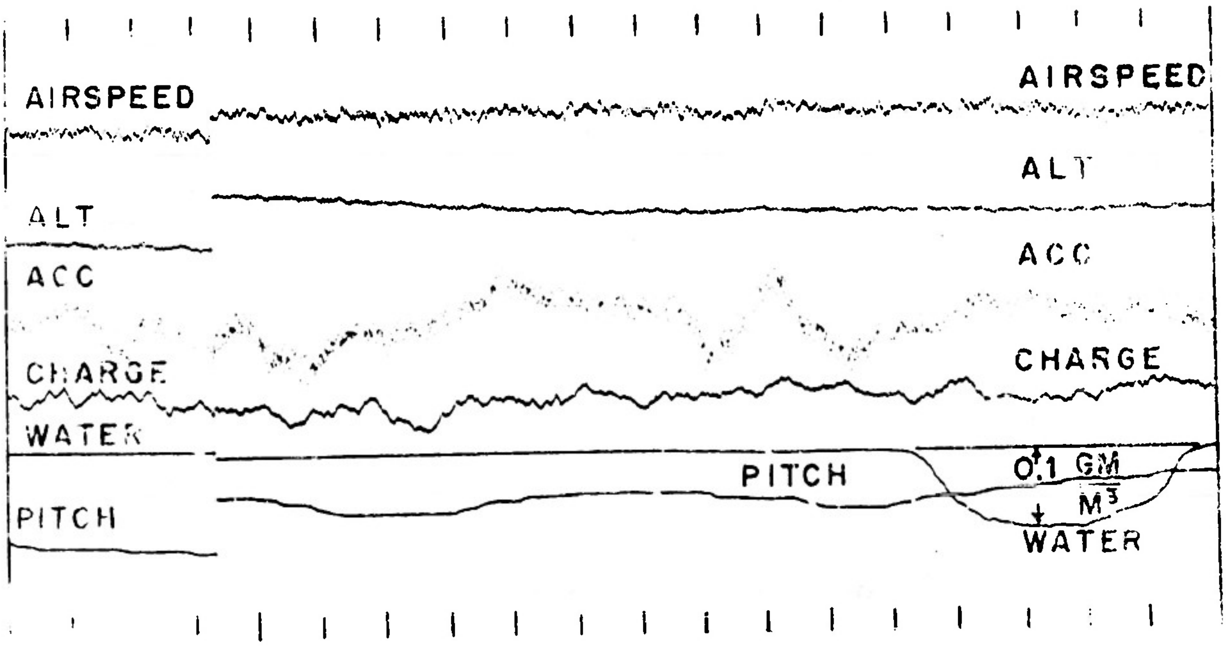

X'S FOR TYPICAL TRADE-WIND CLOUD RUN
⊙ FOR TYPICAL LOW-LEVEL TURBULENCE RUN
$\overline{\Delta n}$ cm/sec^2
100
80
60
40
20
2
6
10
14
18
22
26
30
34
38
42
46
TIME (SECS)

FIG. 3


AIRSPEED
ALT
ACC
CHARGE
WATER
PITCH
AIRSPEED
ALT
ACC
CHARGE
PITCH
0.1 GM/M³
WATER

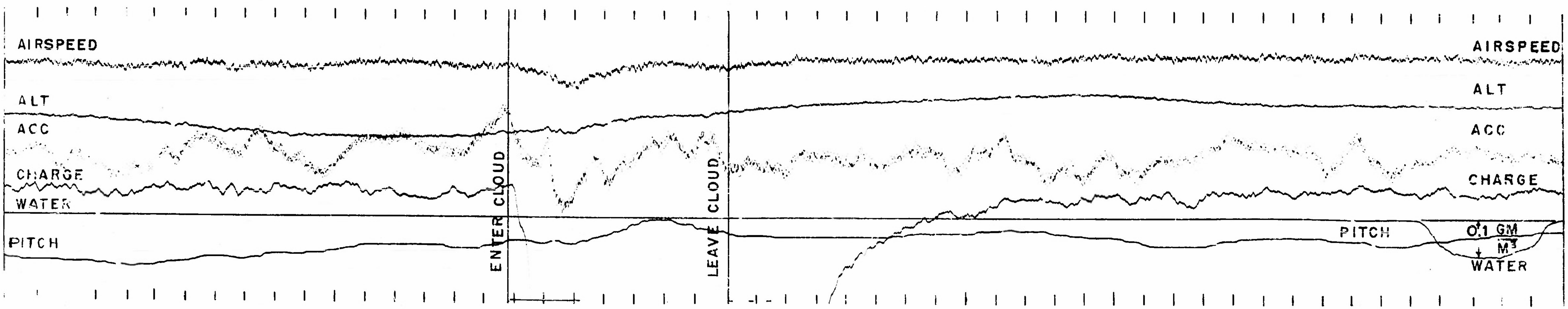

AIRSPEED
ALT
ACC
CHARGE
WATER
PITCH
ENTER CLOUD
LEAVE CLOUD
AIRSPEED
ALT
ACC
CHARGE
PITCH
0.1 GM/M³
WATER

FIG. 4

FIG. 5

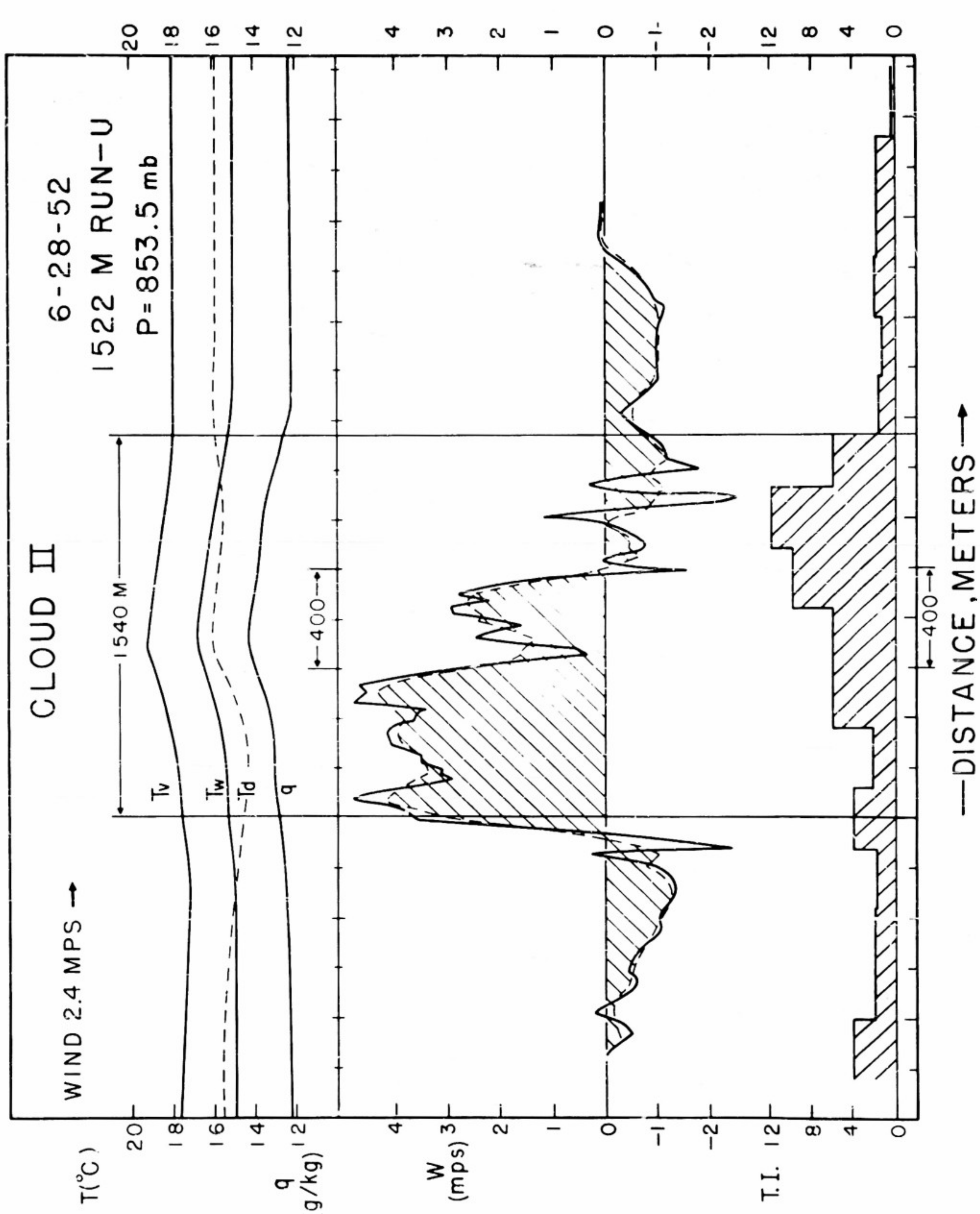

CLOUD II
6-28-52
1522 M RUN-U
P = 853.5 mb
WIND 2.4 MPS →
1540 M
400
Tv
Tw
Td
q
T(°C)
q (g/kg)
W (mps)
T.I.
—DISTANCE, METERS—

FIG. 6

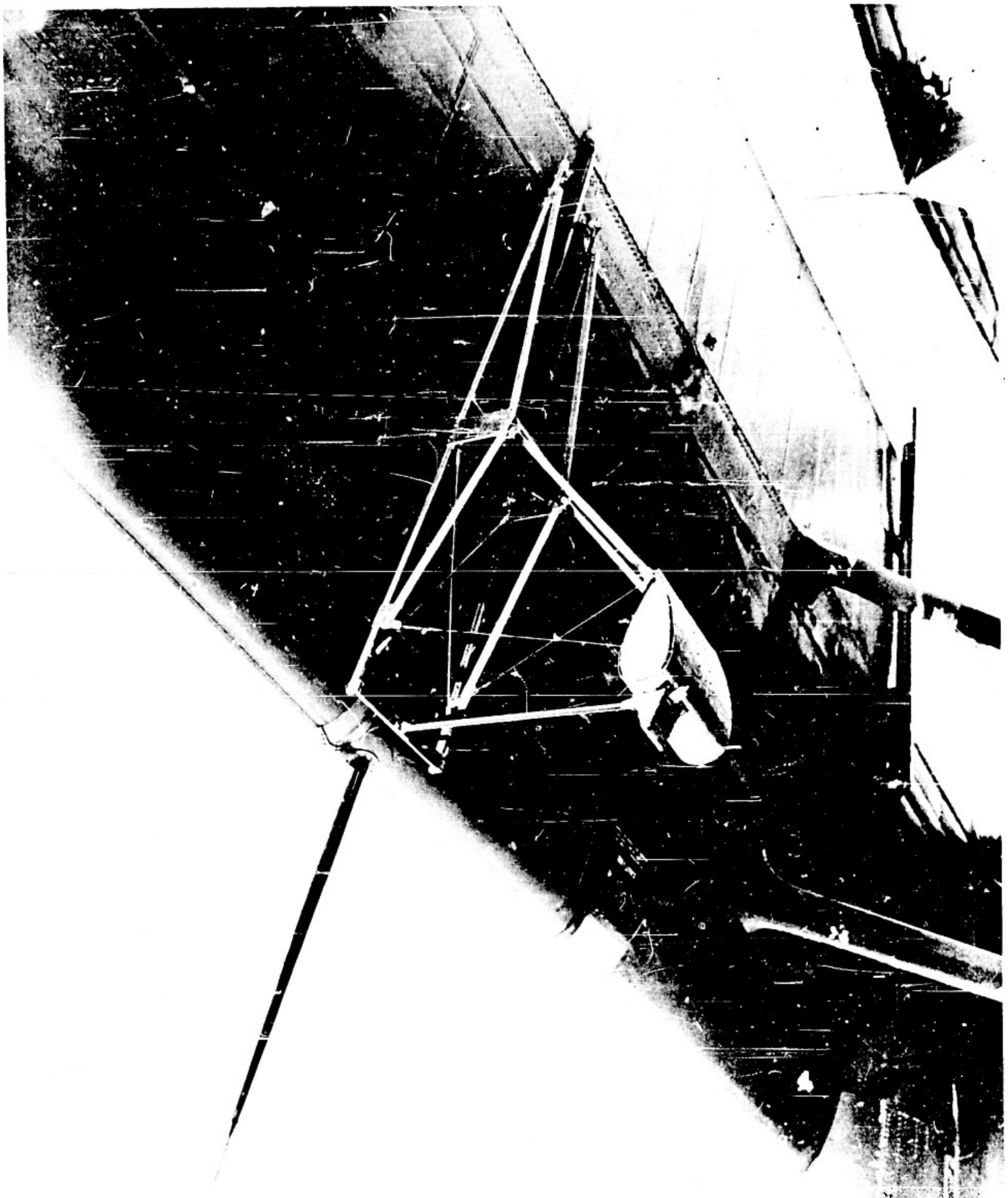


FIG. 7

FIG. 8

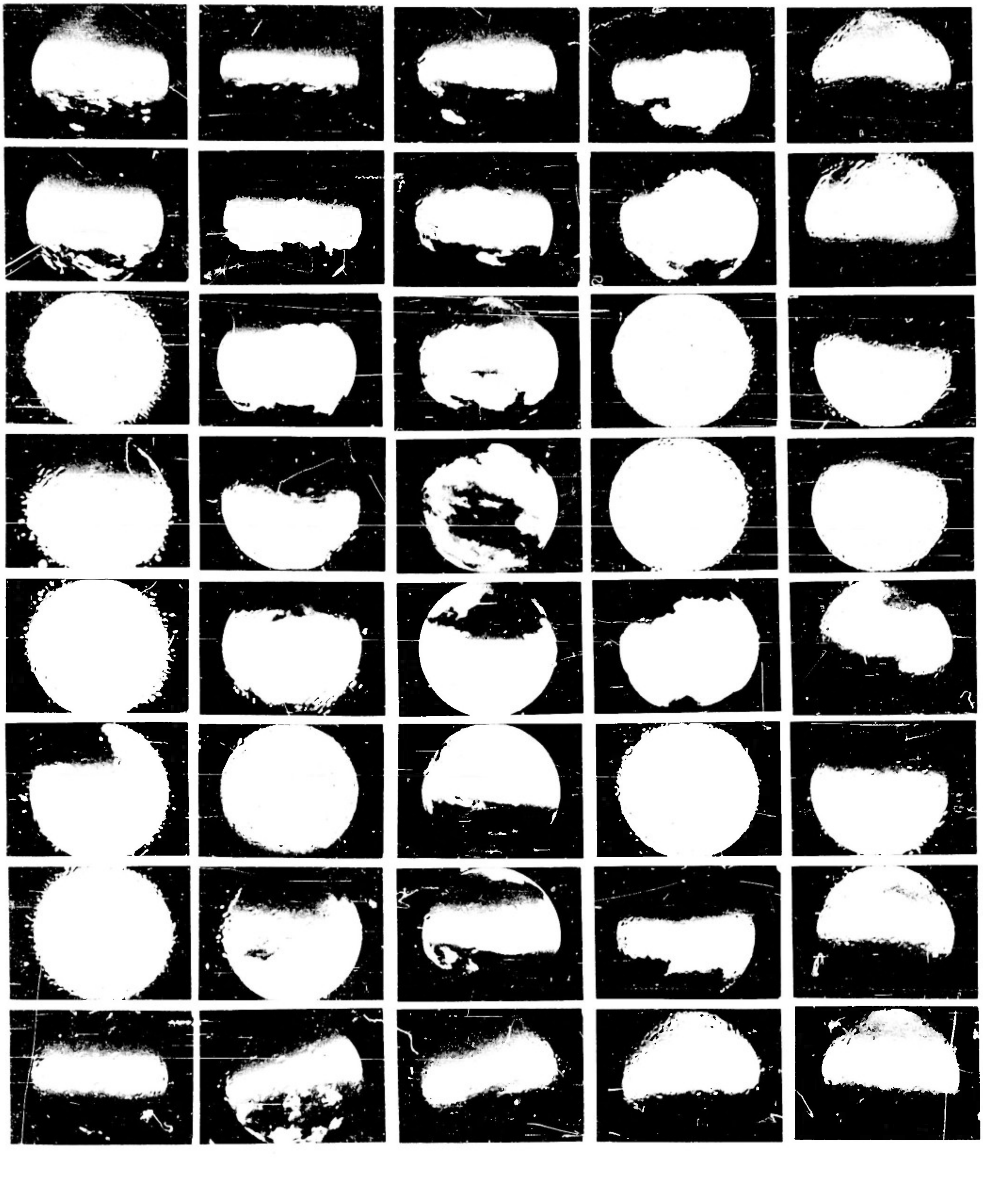


FIG. 9

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